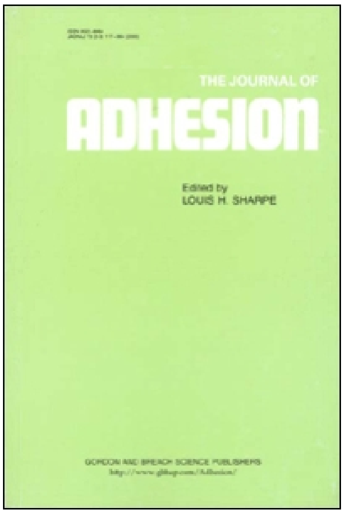

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Chiaki Sato[a]; Kozo Ikegami[a]
[a] Precision and Intelligence Laboratory, Tokyo Institute of Technology, Yokohama, Japan

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Strength of Adhesively-Bonded Butt Joints of Tubes Subjected to Combined High-Rate Loads

CHIAKI SATO* and KOZO IKEGAMI

Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226, Japan

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The dynamic strength of adhesively-bonded joints was investigated experimentally. The strength of the bonded joints under combined high rate loading was measured using the clamped Hopkinson bar method. Tubular butt joints bonded by epoxy resin were used for the experiment. Combined stress waves of tension and torsion were applied to the specimens. The strength of the adhesively-bonded joint was determined by measuring the stress waves propagated in the load output tube of the specimen. It was found that the dynamic strength of the adhesive joints was greater than the static strength under tensile and shear load.

Keywords: Adhesion; dynamic strength; high rate loading; combined stress; fracture; Hopkinson bar

INTRODUCTION

In recent years, the reliability of adhesively-bonded joints has become important because their use has expanded to include hostile environments. Since adhesively-bonded joints are widely used in aircraft and automobile structures, the crash worthiness of the products has to be proven. Thus, the dynamic strength of joints subjected to high-rate loading should be investigated.

*Corresponding author. Tel.: 81-45-924-5062, Fax: 81-45-924-5961, e-mail: csato@pi.titech.ac.jp

Much research has been conducted on the critical energy to fracture of adhesives. However, few investigations on evaluation of dynamic strength of the joints have been carried out [1 – 5]. Harris *et al.*, conducted impact tests of single-lap joints which consisted of aluminum alloy adherends bonded by epoxy adhesives [1]. Kinloch *et al.*, examined the fracture energy, G_{IC}, of an adhesive layer using single-edge notched three-point bending (SENB) specimens and an instrumented testing machine with a pendulum striker [2]. Shear strength of joints under impact loading was obtained experimentally by Lataillade *et al.*, using Hopkinson bar equipment [3] and tensile equipment with an inertial wheel [4]. The shear strength of joints was also measured by Yokoyama *et al.*, using pin-and-collar specimens and a split Hopkinson bar technique [5]. Joints used in structures, however, are often subjected to a combined state of tensile and shear stress components. Therefore, in order to estimate joint strength for dynamic loading, it is necessary to clarify the strength of bonds under combined stress states.

In this paper, the dynamic strength of adhesively-bonded joints is investigated experimentally. High-rate combined loads of tension and torsion were applied to bonded tubular butt joints using a split Hopkinson bar including clamping equipment. Then, the dynamic strength of the joint was experimentally determined. The static strength of the specimen was also experimentally determined and compared with the dynamic strength.

EXPERIMENTAL EQUIPMENT

The experiments were conducted using a high-rate loading machine including a biaxial Hopkinson bar and clamping equipment shown schematically in Figure 1. The Hopkinson bar was made of chrome-molybdenum steel, and had a diameter of 20 mm and a length of 1200 mm, as shown in Figure 2.

The specimen consisted of two steel tubes bonded adhesively using an epoxy resin as shown in Figure 2. A short tube, the so-called "load input tube", was connected to the end of the Hopkinson bar by a screw. The other tube, called the "load output tube", was suspended so that the reflection of stress waves could not occur during the short

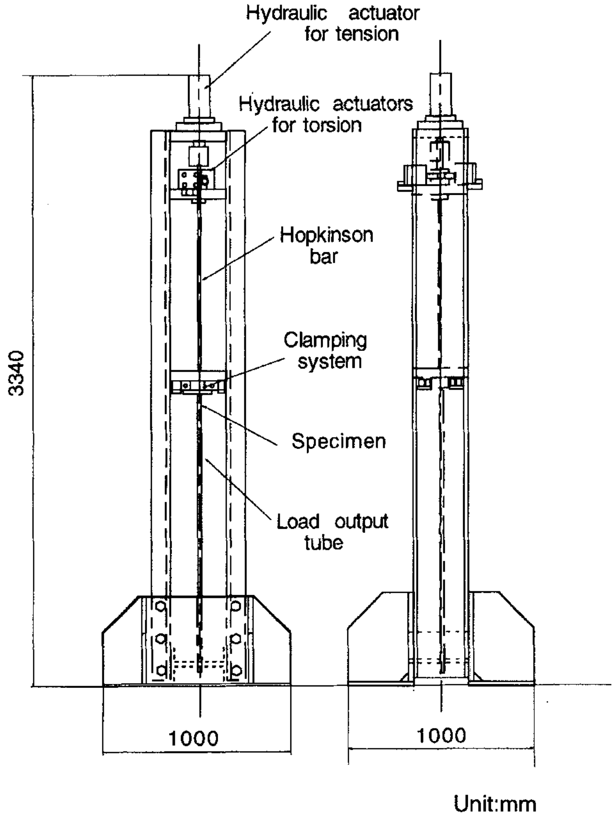

FIGURE 1 Dimensions and configuration of testing machine for combined high rate loading.

period of the experiment. Figure 3 shows the equipment used to clamp the Hopkinson bar. The end of Hopkinson bar was fixed by the clamp teeth. The other end of the Hopkinson bar was connected with jigs for tensile and torsional loading by hydraulic actuators. The actuators could apply combined loads of tension and torsion, 350 kN and 750 N · m respectively, to the Hopkinson bar. Elastic energy was stored in the Hopkinson bar by the combined static load. The sudden release of the clamping equipment gave rise to a transmission of the elastic energy to the specimen as combined stress waves, as shown in Figure 4. The

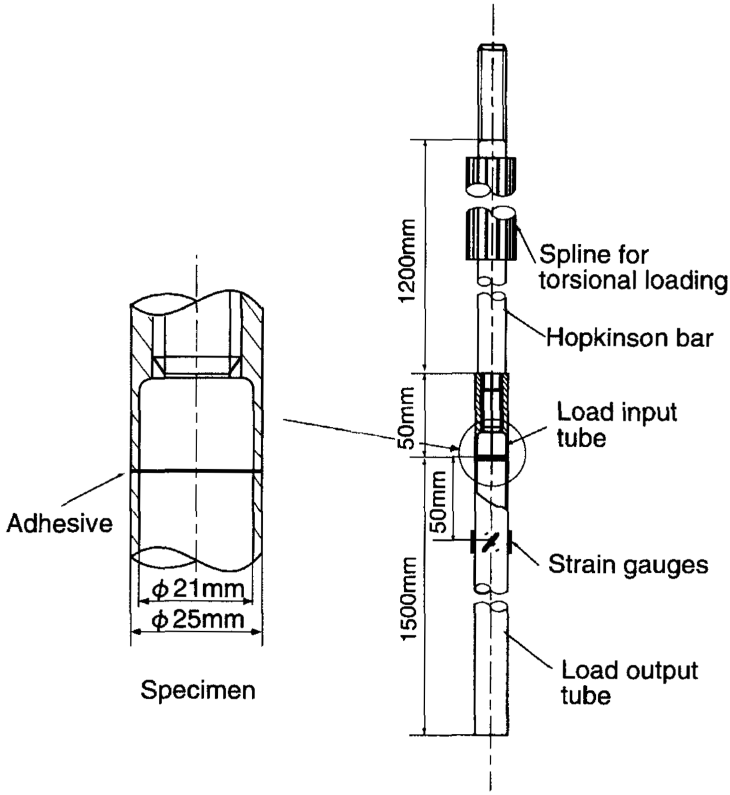

FIGURE 2 Dimensions and configuration of Hopkinson bar and adhesively-bonded specimen.

generated stress wave propagated from the load input tube to the load output tube through the adhesive layer. The stress applied to the adhesive layer, which was induced by the stress wave, was measured as strain variations against time by strain gauges adhered on the surface of the load output tube. The tensile stress wave and the torsional stress wave propagated independently and did not interact.

An appropriate design of the clamping system is most important to experiments involving combined stress waves. The clamping system should have strong fixing and abrupt releasing. In this machine, the

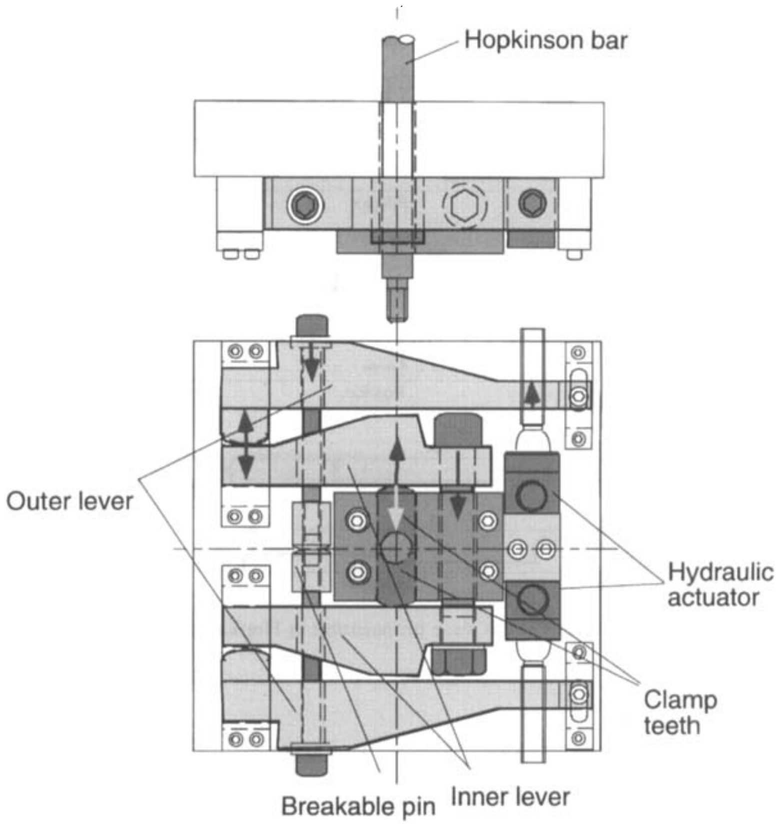

FIGURE 3 Configuration of clamping system of Hopkinson bar.

clamping system consisted of the following parts: teeth, double levers, breakable pin and hydraulic actuators as shown in Figure 3. The teeth clamping the Hopkinson bar were fastened by the hydraulic actuators through the force booster which consisted of the double levers. Pivots of the outer levers were connected using two bolts and a breakable pin made of cast iron shown in Figure 5. When the force applied to the breakable pin by the actuator reached the failure strength of the pin, the pin was broken and the clamp was abruptly released. The failure strength of the pin could be changed by modifying the dimensions of its circumferential notch. The typical strength of the pin shown in

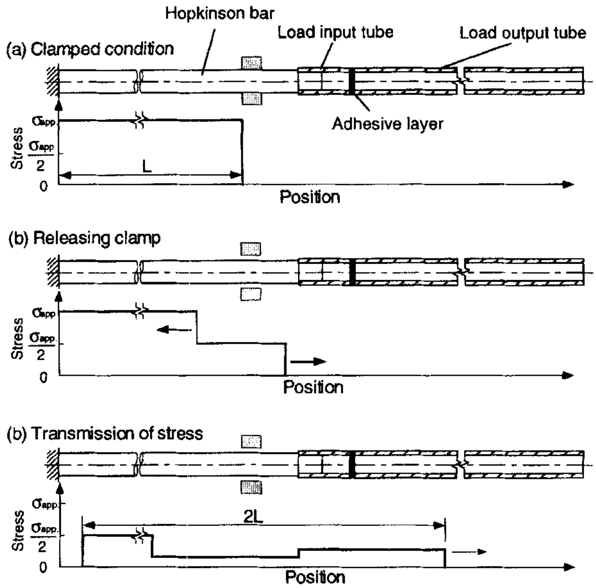

FIGURE 4 Diagram of stress wave propagation in Hopkinson bar and specimen.

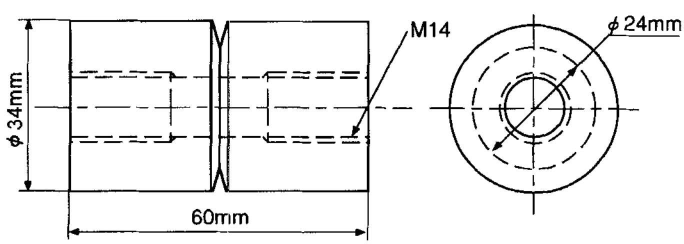

FIGURE 5 Dimensions and configuration of breakable pin.

Figure 5 was 76 kN. The force applied to the pin was boosted up to 200 kN by the inner lever, and was transmitted to the clamp teeth shown in Figure 3. The teeth, the levers and the actuators were set symmetrically so that the Hopkinson bar did not produce a bending moment.

Since the load output tube was suspended vertically, a static load equivalent to the weight of the load output tube was applied to the adhesive layer. This static load was compensated for by using equipment which consisted of pulley blocks and weights as shown in Figure 6.

Strain measurement was performed using metal-foil strain gauges with a length of 2 mm, DC-type strain meters and a digital storage scope. The maximum frequency response of the strain gauges was 400 kHz. This frequency was higher than that of the strain meters, which was 200 kHz. Therefore, the total response of the measuring system was established by the frequency response of the strain meter.

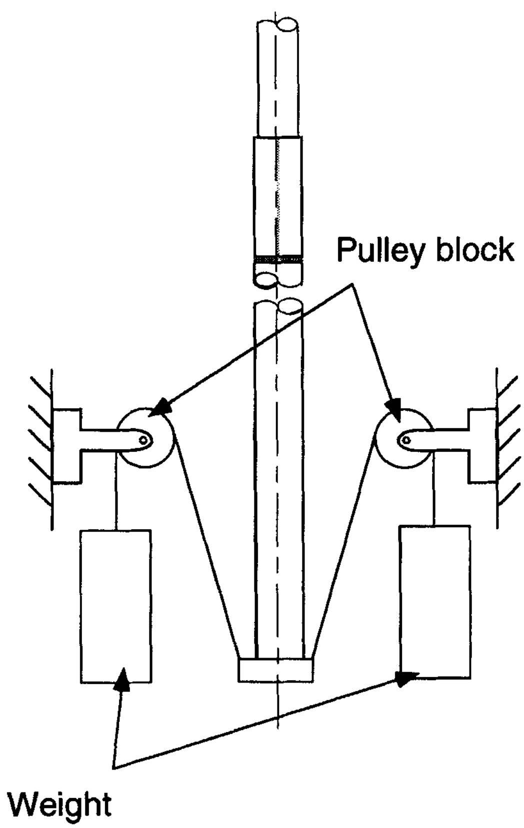

FIGURE 6 Schematic diagram of gravity compensator.

SPECIMEN PREPARATION

The material of the adherends of the tubular butt specimen was carbon steel (S45C). These adherends were bonded using an epoxy adhesive (Scotch Weld 1838, 3M). The bonding procedure for the joints is as follows:

1. Polishing by abrasive paper (#600).
2. Degreasing of the surfaces of the adherends with acetone.
3. Drying the degreased surfaces at room temperature for 10 minutes.
4. Bonding.
5. Curing for 24 hours at room temperature.
6. Post curing for 2 hours at 65°C.

The thickness of the adhesive layer was approximately 50 μm.

PERFORMANCE OF EXPERIMENTAL EQUIPMENT

In order to check the performance of the experimental equipment, several experiments were conducted using specimens that were connected using brazing instead of adhesive bonding. The strength of brazed joints is higher than that of adhesively-bonded joints, so the brazed joints did not fail even when the joints were subjected to the failure stress of the adhesive joints.

Figure 7 shows the stress variation in the specimen after release of the clamp. In the test, a static tensile load was applied to the Hopkinson bar before the clamp release, so dynamic tensile stress occurred in the specimen after the clamp release. The rise time of the stress was longer than that of impact Hopkinson bar equipment. The reason seemed to be the slow release of the clamping system because the system has great inertia.

Figure 8 shows the stress variation in the specimen after release of the clamp. In the test only a static torsional load was applied to the Hopkinson bar before the clamp release, so dynamic shear stress occurred in the specimen after the clamp release. Dynamic tensile stress also occurred in the specimen. However, it was very small and the shear stress was remarkable. As shown in Figure 4, the ideal variation of the stress generated by a Hopkinson bar is a step function in time. However, the

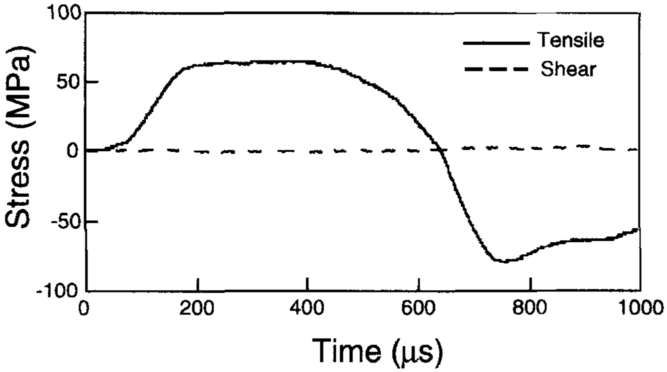

FIGURE 7 Variation of dynamic stresses occurring in a brazed specimen after clamp release. (A static tensile load was applied to Hopkinson bar.)

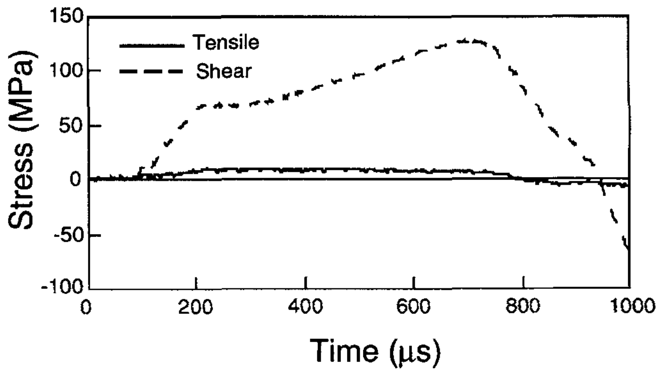

FIGURE 8 Variation of dynamic stresses occurring in a brazed specimen after clamp release. (A static torsional load was applied to Hopkinson bar.)

measured shear stress increased gradually, and showed two steps of increasing. The first step of increasing stress seemed to be due to the slow release of the clamping system. The reason for the second step seemed to be the presence of friction between the Hopkinson bar and the clamping teeth. If the friction was large, the angular velocity of the end of the Hopkinson bar increased slowly after releasing the clamp, so the generated stress in the specimen also increased slowly.

Figure 9 shows the variations of combined stress in the specimen after release of the clamp. In this case, a static combined stress was applied to the Hopkinson bar before the clamp release. In this figure, both tensile stress and shear stress were induced in the specimen. This experiment confirmed that combined loads of high stress rate could be applied to the specimen.

EXPERIMENTAL RESULTS

The experiments on adhesively-bonded specimens were conducted using the test machine mentioned before. Static loads were applied to the Hopkinson bar in order to generate tensile and torsional stresses of 100 MPa, respectively, after release of the clamp. The configuration of the breakable pins was modified to allow the pin to break when the clamping force became 200 kN. Figures 10 to 12 show the stress variation in the specimens. In these figures, the stress values were calculated by applying the elastic constants of the adherends to the obtained strain value.

Figure 10 shows the results of a tensile test. In the test, static tensile loads were applied to the Hopkinson bar before the clamp release. After the clamp release, only tensile stress increased during the initial stage and the stress showed a peak value of 82 MPa at 240 μs. Since the

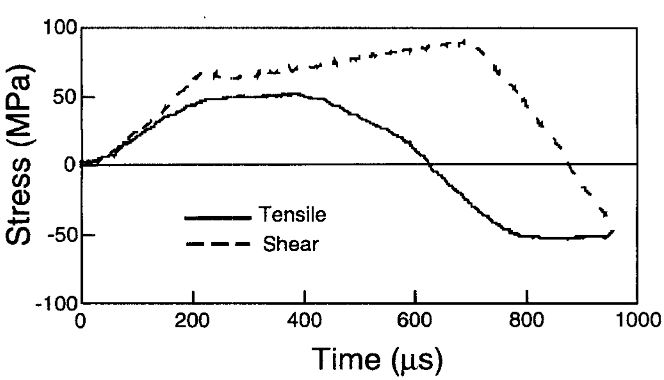

FIGURE 9 Variation of dynamic stresses occurring in a brazed specimen after clamp release. (A static combined load was applied to Hopkinson bar.)

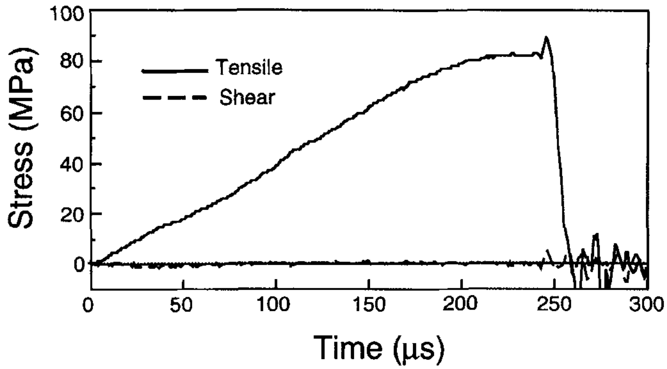

FIGURE 10 Variation of dynamic stresses occurring in an adhesively-bonded specimen after clamp release. (A static tensile load was applied to Hopkinson bar.)

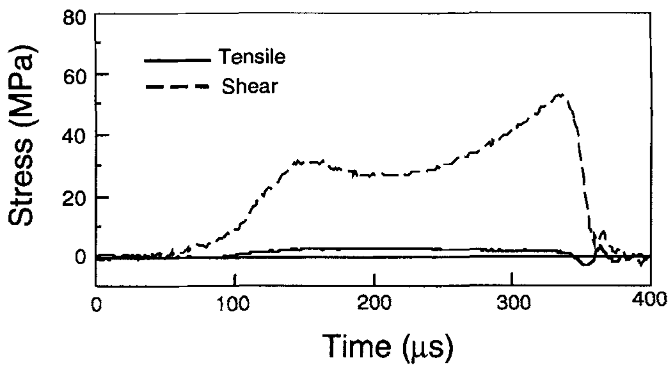

FIGURE 11 Variation of dynamic stresses occurring in an adhesively-bonded specimen after clamp release. (A static torsional load was applied to Hopkinson bar.)

stress decreased suddenly after the peak, this joint must break at the maximum stress value. The peak value of the stress was defined as the dynamic strength of the joint.

Figure 11 shows the stress variation when only a torsional load was applied to the Hopkinson bar. Although this stress variation had two peaks, the second peak was greater than the first. Thus, it was assumed that the second peak indicated the fracture of the joint at 52 MPa.

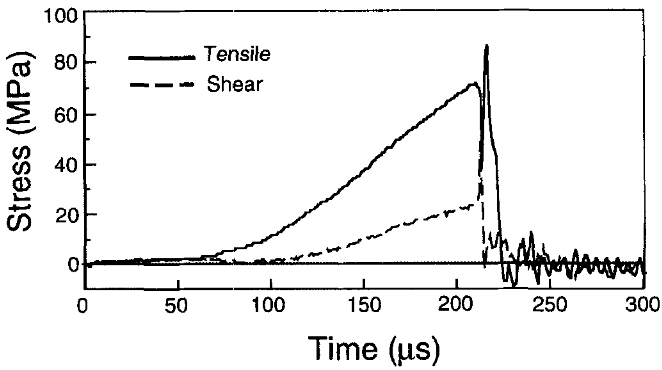

FIGURE 12 Variation of dynamic stresses occurring in an adhesively-bonded specimen after clamp release. (A static combined load was applied to Hopkinson bar.)

Figure 12 shows a case of combined dynamic loading. This result indicates a proportional loading of tensile and shear stress of 3 : 1.

In Figures 10 and 12, there were small fluctuations of stress after joint fracture. However, these might be ignored because they appeared to be the result of the influence of a complicated stress wave caused by anti-symmetrical fracture of the joints.

Several combined loading tests were conducted, changing the load components of tension and torsion. The fracture stress values from these tests are shown in Figure 13. In this figure, the black circles indicate the stress values of joint fractures, the lines indicate the loading paths, and the numbers indicate the time to fracture. The dynamic strength of the joints depended on both components of the stresses. Some loading paths were not straight in the figure. In these cases, the loading paths deviated from a straight line and curved to the shear direction because the variation of the shear stress showed the two steps of increasing as mentioned in the previous section. The stress rates of these examinations were within the range of 10^{11} Pa/s $\sim 10^{12}$ Pa/s, and the time duration of loading within 150 μs $\sim$ 300 μs. These stress rates are higher than those of ordinary dynamic testers powered by hydraulic systems, although they are lower than that of impact Hopkinson bar equipment.

Figure 14 shows curves fitted to the experimental results using the Tresca law and the von Mises law. The Tresca law is described by the

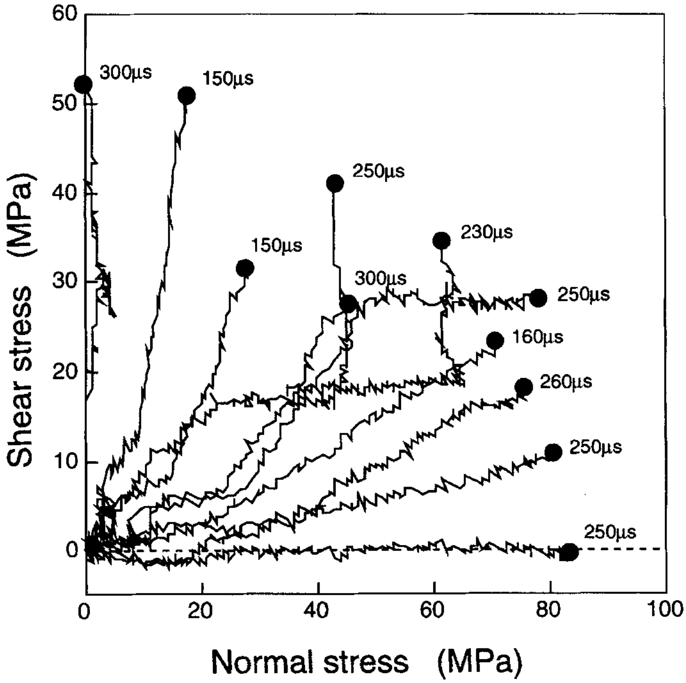

FIGURE 13 Loading path and fracture stress of adhesive joints under dynamic loading.

following formula:

$$\sigma^2 + 4\tau^2 = \sigma_y^2 \tag{1}$$

and the von Mises law is described as:

$$\sigma^2 + 3\tau^2 = \sigma_y^2 \tag{2}$$

Here, σ and τ indicate the applied stress and σ_y indicates the strength parameter of the material. In the figure, the dashed curves are fitted by the tensile strength, σ_y, of the joints. The solid curves are fitted by the shear strength, τ_y. The von Mises law appears to describe the experimental results more accurately than the Tresca law.

Figure 15 shows an equation of 2nd-order polynomials applying a non-linear least squares method of fit the data. The form of the

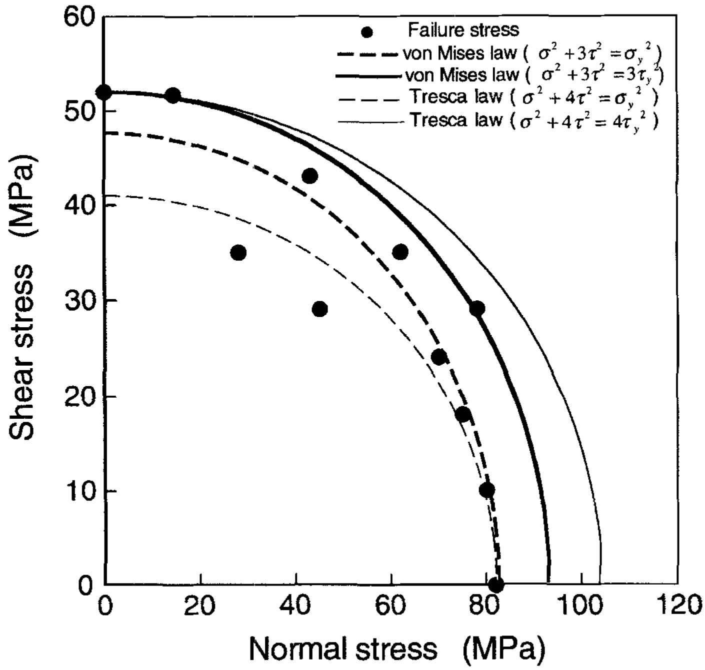

FIGURE 14 Approximation by Tresca and von Mises laws.

polynomial equation is as follows:

$$\tau_d'^2(\sigma_d - \sigma_d') + \sigma_d'\tau_d^2 = 0 \tag{3}$$

Here, σ_d and τ_d indicate the applied stress, and σ_d' and τ_d' signify the dynamic strength obtained experimentally. In this experiment, σ_d' was 84 MPa and τ_d' was 52 MPa. Although the polynomials have no physical meaning, they show good agreement with the experimental results. Thus, the formula can be used for actual design of joints as an approximation of the bond strength. The shear strength of the bond under static loading increases when a small compressive stress is applied simultaneously [6]. It seems that increased shear strength occurs also under dynamic loading. The formula of the polynomials has a useful aspect because it can describe the increasing of the bond strength. The Tresca law and the von Mises law both show a decline of the shear strength under compressive stress.

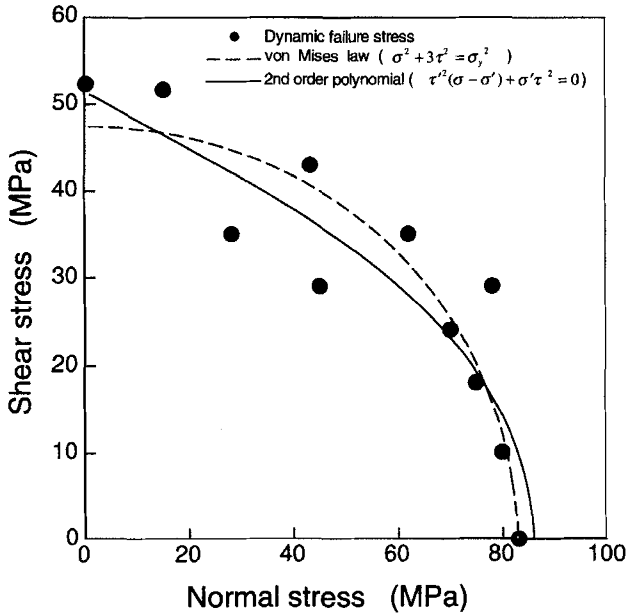

FIGURE 15 Strength law under high-rate loading approximated by von Mises law and 2nd order polynomial equation.

The static strength of the adhesively-bonded joints was measured using the same specimens as for the dynamic examinations. A quasi-static load was applied to a specimen which was fixed at the end of the load output tube. The strain induced in the specimen was measured using strain gauges applied to the surface of the load output tube, and the applied stress was calculated using elastic constants of the specimen and measured strain values. The static strength is shown in Figure 16. The open circles in the figure indicate the static strength of the joints, and the curves are fitted by the following equation which is similar to Eq. (3):

$$\tau_s'^2(\sigma_s - \sigma_s') + \sigma_s'\tau_s^2 = 0 \quad (4)$$

Here, σ_s indicates the applied tensile stress, and τ_s indicates the applied shear stress; σ_s' and τ_s' signify the parameters of static strength obtained experimentally. In these experiments, σ_s' and τ_s' were determined as

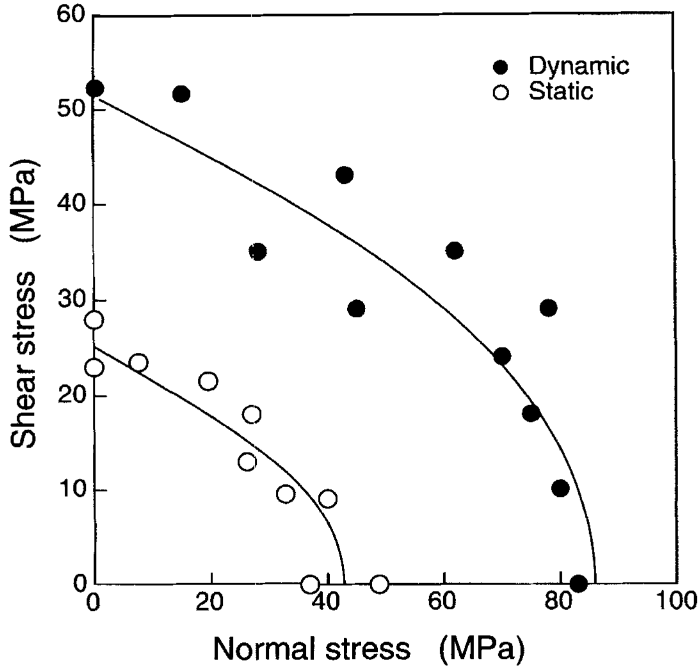

FIGURE 16 Comparison between dynamic and static strength of joints.

42 MPa and 25 MPa, respectively. The dynamic strength obtained was about twice as high as the static strength.

Cohesive fracture was observed mainly on the adhered surfaces of the specimens subjected to static loads. However, cohesive and (visually) interfacial fractures were observed on the specimen subjected to dynamic loads.

CONCLUSION

In this work, the dynamic strength of adhesively-bonded tubular butt joints under combined high-rate loading was investigated experimentally using Hopkinson bar equipment developed by the authors. The following results were obtained.

1. The dynamic strength of the joints was larger than the static strength under tensile, torsional and all cases of combined loading.
2. The failure criterion of the bond under high-rate loading could be described more accurately by the von Mises law rather than the Tresca law.
3. The experimental results of the dynamic strength could be approximated by a simple equation of 2nd order polynomials which was useful for the actual design of joints.
4. Cohesive and (visually) interfacial fractures were observed on the adherend surfaces of the specimen in the dynamic test although the cohesive fracture was remarkable in the static tests.

References

[1] Harris, J. A. and Adams, R. D., *Proc. Instn. Mech. Engrs.* **199**, 121 (1985).
[2] Kinloch, A. L. and Kodokian, G. A., *J. Adhesion* **24**, 109 (1987).
[3] Lataillade, J. L. and Keisler, C., Charobonnet ph., *Preprints of EURADH'92 Conference* (Karlsruhe, Germany, 1992), pp. 584–589.
[4] Cayssials, F. and Lataillade, J. L., *J. Adhesion* **56**, 281 (1996).
[5] Yokoyama, T. and Shimizu, H., *Proceedings of ATEM'97 Conference* (Wakayama, Japan, 1997), pp. 221–226.
[6] Sato, C. and Ikegami, K., *Int. J. JSME, Ser. A* **37**, 282 (1994).